Determination of spin axis orientation of Geosynchronous objects using space-based sensors: an initial feasibility investigation

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Abstract

The spin axis of a rotating satellite can be determined by studying the rate of change of the observed spin rate as a function of the satellite's position in its orbit. The observed spin rate change is largest when the rate of change of the sun-satellite-observer angle is largest. Application of this method is problematic for deep-space objects due to the slow rate of change of this angle, however some assumptions can be made to make the problem tractable. Alternatively, since space-based sensors in Low Earth Orbit are moving much faster than ground-based sensors, use of such a sensor has the potential to expand the number of objects for which the spin axis can be determined. This paper explores both approaches. First, a ground-based – and assumption-based - method is used to determine the spin state of rocket bodies in deep-space. This is followed by a comparison of the rate of change of the spin rate that would be observed by both a ground-based and a space-based sensor. This comparison both illuminates the issues with using a ground-based sensor, and the potential of a space-based sensor. The use of the upcoming NEOSSat spacecraft – to be launched in Q2 2011 – to exploit this potential is explored.

1. Introduction

Earth's orbital environment is becoming increasingly cluttered due to the increased rate of satellite launches over time, and on-orbit incidents such as the Breeze-M explosion in 2007 and the Iridium 33-Cosmos 2251 collision in 2009. The Iridium/Cosmos collision of 2009 is an example of the consequences of this increasingly cluttered environment, and serves to underline the importance of mitigating and reducing the number of objects on-orbit.

The consequences are of even greater concern for the geostationary belt, that unique realm where objects will stay in place over a position on the Earth's surface with only a minimum of intervention and are thus preferred for many communications and Earth-observing missions. Unfortunately, any debris generated in the geostationary belt will move through the belt, placing other objects in the belt at risk; examples of such debris include the derelict Telstar 401 and Galaxy 15 spacecraft.

The uniqueness of the geostationary belt, coupled with the persistence of debris that exists in that orbit, leads to the observation that it would be desirable to remove debris objects from the belt before they adversely affect an operational system. While responsible satellite operators routinely dispose of end-of-life satellites by placing them in graveyard orbits above the GEO belt, objects that fail prematurely cannot currently be moved. However, robotic servicing technologies are rapidly maturing, leading to the potential that – in the future – missions can be launched to rendezvous with debris objects in the GEO belt and boost these objects into graveyard orbits away from harm [1,2].

An issue often overlooked in these discussions is the difficulty in robotically grasping an object that is likely tumbling uncontrolled. Both the angular velocity and spin vector orientation of the object need to be known before launch of a captivation mission in order to plan the rendezvous and intercept that will allow for the object to be captured using a suitable attachment point (such as the Marman clamps or apogee kick motor nozzles). This creates a new problem for space surveillance sensors in order to determine the spin state of the object, rather than simply the orbital position of the object as is usually performed during routine, metric space surveillance tasking.

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14. ABSTRACT

The spin axis of a rotating satellite can be determined by studying the rate of change of the observed spin rate as a function of the satellite?s position in its orbit. The observed spin rate change is largest when the rate of change of the sun-satellite-observer angle is largest. Application of this method is problematic for deep-space objects due to the slow rate of change of this angle, however some assumptions can be made to make the problem tractable. Alternatively, since space-based sensors in Low Earth Orbit are moving much faster than ground-based sensors, use of such a sensor has the potential to expand the number of objects for which the spin axis can be determined. This paper explores both approaches. First, a ground-based ? and assumption-based - method is used to determine the spin state of rocket bodies in deep-space. This is followed by a comparison of the rate of change of the spin rate that would be observed by both a ground-based and a space-based sensor. This comparison both illuminates the issues with using a ground-based sensor, and the potential of a space-based sensor. The use of the upcoming NEOSSat spacecraft ? to be launched in Q2 2011 ? to exploit this potential is explored.

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One way to determine this information is to use a method – dubbed the “Epoch Method” [3] – that uses changes in the observed (synodic) photometric period of an unresolved object. This method has been applied to Resident Space Objects (RSOs) in elliptical orbits near perigee, but is problematic for use for objects in deep-space. The issue with deep-space objects is that the relative rate of change in the sun-object-observer angle is not fast enough to observe changes in the periods of the objects in comparison to the rotational rate of the object itself.

Possible solutions to these issues are to a) make some assumptions about the objects and their spin state, or b) to increase the rate of change of the sun-object-observer angle by placing the observer in orbit also. Both of these possibilities will be explored in this paper.

2. The Epoch Method

The Epoch Method has been described in a number of papers [3,4] and will not be belabored here. Instead, a brief summary will be presented.

A spinning orbital object will have two types of spin periods. The first – the “sidereal period” – is the time it takes for the object to complete one rotation with respect to the stars. The second period – the “synodic period” – is the time it takes for the object to go from one orientation with respect to the observer back to that same orientation with respect to the observer. The reason that the synodic and sidereal periods differ is that during the time it takes for the satellite to complete one synodic period the observer has moved due to the spin of the Earth, and the satellite has moved in it’s orbit. This is illustrated in Fig. 1.

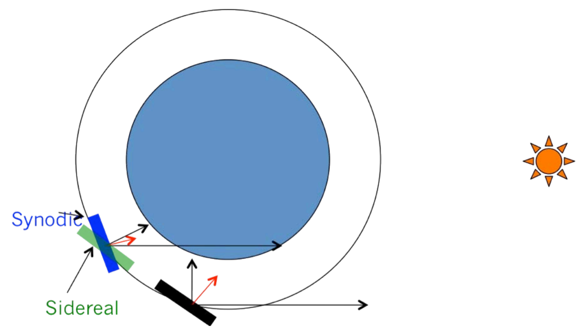

Figure 1: An illustration of the difference between synodic (observed) and sidereal (true) period for a spinning flat plate. The phase-angle bisector is shown in red.

The difference between the synodic and sidereal periods is a result of several factors including the relative motion of the observer and target, the orbital velocity of the satellite, the spin rate of the satellite, and the orientation of the satellite’s spin axis. The key quantity, the one that draws all of these aspects together, is the phase-angle bisector (PAB; the vector that bisects the sun-object-observer angle). The important angles are show in Fig. 2.

Hall et al. [4], applied the epoch method to determine the spin state of the IMAGE satellite. The observed synodic frequency, ω_{syn}, is related to the sidereal spin frequency, ω, and the projection of the PAB, Ψ, by

$$\omega_{syn}(t,\omega,\theta,\phi) = \omega - \frac{\partial\Psi(t,\theta,\phi)}{\partial t}$$

where (θ, ϕ) are the orientation of the spin axis in some useful coordinate system (typically equatorial J2000).

In their observations of the IMAGE satellite, the PAB was moving sufficiently fast in comparison to IMAGE’s 0.5-rpm revolution rate that a noticeable modulation of the photometric period was observed.

The Epoch method works well for a fast moving PAB, but in the case of a slower moving PAB – such as for a deep-space object - this approach is problematic. Two approaches can be used to applying this method to deep-space objects: either reduce the number of unknowns by making assumptions about the shape and/or rotation of the object, or increase the velocity of the observer, thus increasing the rate of the satellite-observer vector (**O***). We shall discuss both these approaches below.

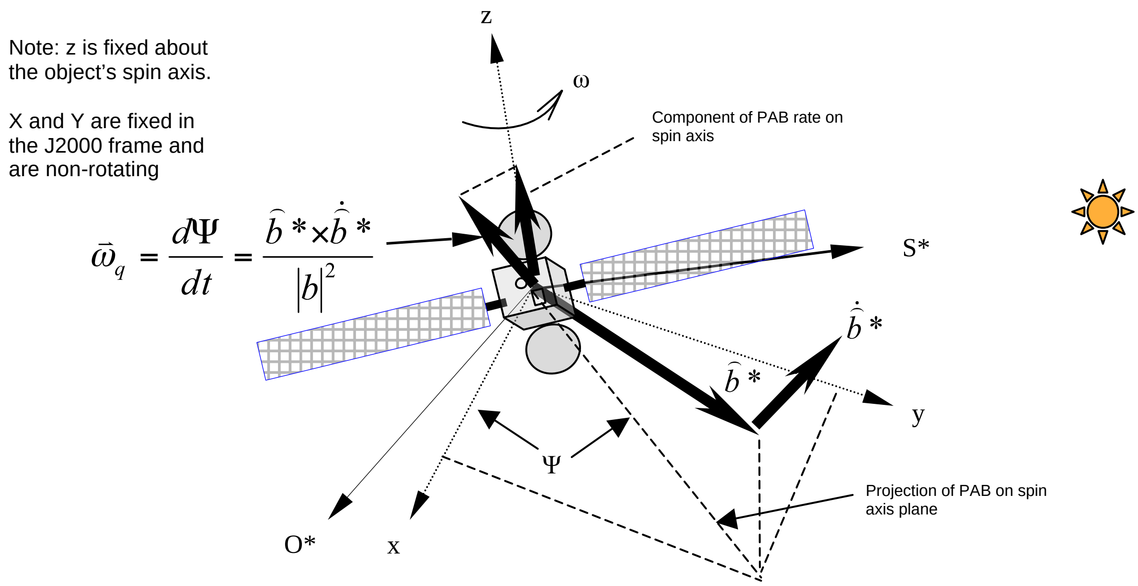

Figure 2: The important geometry and angles for the situation described herein. **O*** is the object-observer unit vector, **S*** is the object-sun unit vector, and **b*** is the phase angle bisector. The upper vector labeled $\boldsymbol{\omega_q}$ is actually the apparent, instantaneous rotation of **b*** and its projection onto the spin axis is shown. The object is spinning at a frequency ω around the z-axis, while the azimuthal component of the phase angle bisector, Ψ moves in the plane perpendicular to the spin axis.

3. Simplifying Assumptions for Cylindrical Objects

de Pontieu [6] used a modified version of the Epoch Method where he makes the simplifying assumptions.

- the object is a cylinder (with body axis a) that is undergoing an end-over-end tumble ($\hat{z} \bullet \hat{a} = 0$), reasonable for a rocket body), and
- the observer sees only specular glints ($\hat{b} \bullet \hat{a} = 0$), and
- that the rotation axis direction and rotational period is constant

de Pontieu observed objects in Low Earth Orbit, where $\partial\Psi/\partial t$ is large and charges significantly during a 15 minute pass. For deep-space objects, $\partial\Psi/\partial t$ is small, and long observation periods (on the order of 2 hours, albeit not necessarily contiguous) are required.

The Process

The process used here compares the time of arrival of a series of observed glints with the times predicted by a series of models that assume a sidereal frequency (Ω) and associated spin axis orientation (α,δ). The goal of this process is to find the model (Ω, α,δ) which minimizes the difference between the observed glint times and the predicted (model) glint times; this model is the best estimation (subject to our assumptions) of the spin state of the object.

The objects observed are a series of SL-6 rocket bodies and old Anik C/D cylindrical satellites. These objects were chosen because

a) they are long cylindrical bodies and, as such, are likely undergoing an end-over-end tumble (thus satisfying the assumption that $\hat{z} \bullet \hat{a} = 0$),
b) have largely specular reflections (thus satisfying the assumption that $\hat{b} \bullet \hat{c} = 0$) and
c) are located in deep-space.

The objects were observed using the CASTOR telescope [6] located at the Royal Military College (RMC) of Canada located in Kingston, Ontario. The data were obtained in Star Stare Mode (SSM) in order to capture the relatively fast glints using a camera that was not made for fast imaging. An example image is shown in Fig. 3.

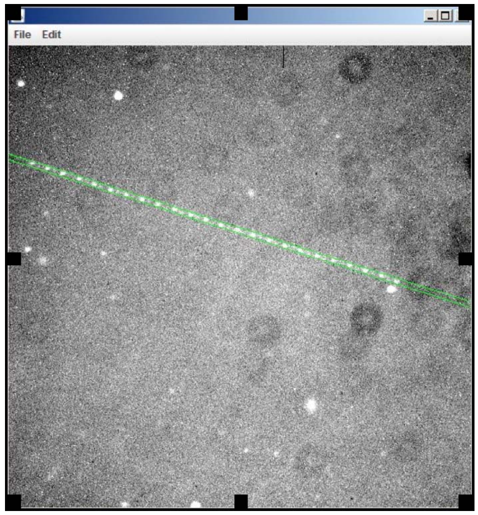

Figure 3: An example of a series of glints from an SL-6 rocket body, which lie between the two green lines, collected using the RMC sensor. "Dust doughnuts" are evident in the image.

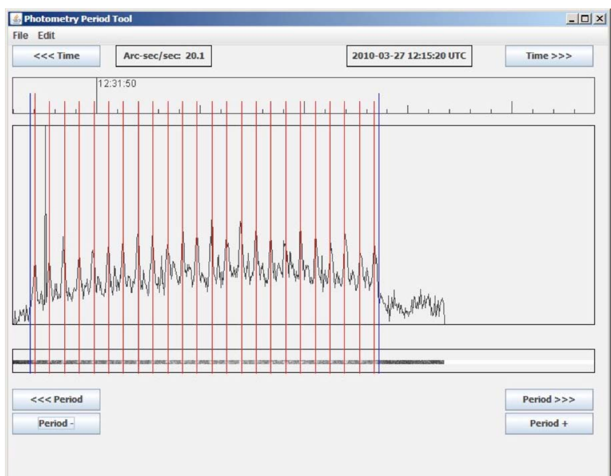

Figure 4: An example light curve from a single SSM image of a tumbling SL-6 rocket body. The red lines denote the glint peaks identified by the processing software.

After data collection, the times of the glints are measured (see Fig. 4) and the sidereal period is initially estimated by averaging the periods measured from the whole dataset (T_{avg}). Using this period, the spin axis of the cylinder is varied (in one degree increments) between Right Ascension = (0°, 360°) and Declination = (-90°, 90°) and the glint times are predicted for each orientation. For each observed glint the time of the nearest predicted glint (at each orientation) is found and the difference between the two are recorded. The sum of absolute value of the time differences for each orientation is found, and becomes the “score” for that combination of assumed (Ω, α,δ). An example of the results of the process for a single trial sidereal period is shown in Fig. 5.

This process is repeated for a range of trial periods between (T_{avg} - 0.020s) < T < (T_{avg} + 0.020s), in increments of 0.001s. This process creates a data cube containing the “score” – related to the deviations between the predicted and observed glint times – for each tested period and spin axis orientation. The point in the cube that contains the lowest “score” corresponds to the most likely (given our assumptions) sidereal period and spin axis orientation.

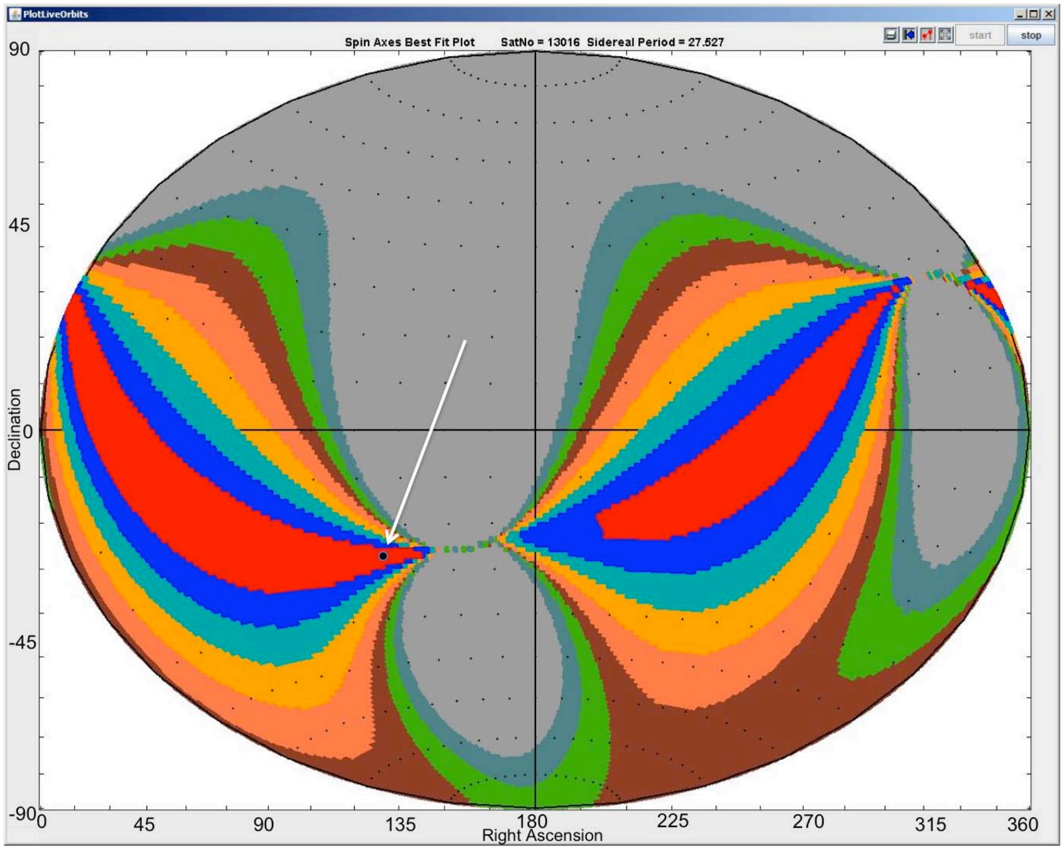

Figure 5: An example of the differences between the observed and predicted glint times as a function of spin axis orientation for a single assumed sidereal period. The white arrow points to a small black point indicating the minimum value of these differences, and the associated orientation of the spin axis.

The preliminary results for the sidereal periods and spin axis orientations of a small number of objects are listed below. These preliminary results show an approximate alignment of the spin axes with the solar direction, which may indicate a bias problem with the analysis method. If the alignment is real, then it may show that the spin axes of tumbling SL-6 cylinders are aligned in the solar direction due to solar radiation pressure. Independent observations and analyses are welcomed to help resolve this issue.

		Primary Solution			**Secondary Solution**			
SSN #	**Date**	**$T_{sidereal}$ (s)**	**RA (°)**	**Dec (°)**	**$T_{sidereal}$ (s)**	**RA**	**Dec**	**Type**
09850	2010-08-07	19.318	119	-23	19.330	285	21	SL-6
09850	2010-08-14	19.316	289	22	19.318	114	-27	SL-6
09850	2010-08-19	19.319	113	-20	19.318	291	25	SL-6
13016	2010-07-17	27.380	126	-25	27.368	306	25	SL-6
13016	2010-07-26	27.446	129	-22	27.440	281	03	SL-6
13016	2010-08-07	27.527	125	-27	27.529	300	07	SL-6
15223	2010-08-07	65.805	151	-26	65.804	334	26	SL-6
15383	2010-08-17	02.822	296	-14	2.822	136	45	Anik D2

4. The View From Space

In order to address the inability to directly use the Epoch Method on a deep-space object using a ground-based sensor, the problem was simplified by making several shape-based assumptions. It is not currently clear how reliable the results may be, and the assumptions reduce the types and numbers of objects for which the spin axis state can be found. The desire is thus to find a way that the Epoch Method can be used without making shape based assumptions about the object under study.

The inability to use the Epoch Method stems from the slow rate of motion of the PAB when observing the deep-space objects from the ground compared to the nominal spin rate of the object under study. Recognizing that a sensor placed in LEO moves much faster than the ground-based sensor, and thus that the PAB will have a larger rate of motion, the question now becomes whether – and under what conditions - the space-based sensor will be able to collect data that can be used to apply the Epoch Method to a more general set of deep-space objects. This question is not simply of theoretical curiosity of course; the next few years will see several optical space surveillance sensors placed on-orbit, including the Near Earth Orbit Surveillance Satellite (NEOSSat; a satellite owned jointly by Defence Research and Development Canada and the Canadian Space Agency) which will be placed on-orbit in Q2, 2011 [6].

In order to get a first-order understanding of this question a simple computer model was created. An object was assumed that was rotating once every 1000s (the sidereal period), and which has the spin axis pointing toward RA = 270 degrees, Dec = +45 degrees. As a baseline, the synodic period of this object was calculated once a minute for 14 hours, assuming that the object was in a geostationary orbit and the observer was located in Ottawa, Canada. For comparison, the same values were calculated assuming that the same object was observed from the assumed orbit for NEOSSat (800km altitude, dawn-dusk orbit).

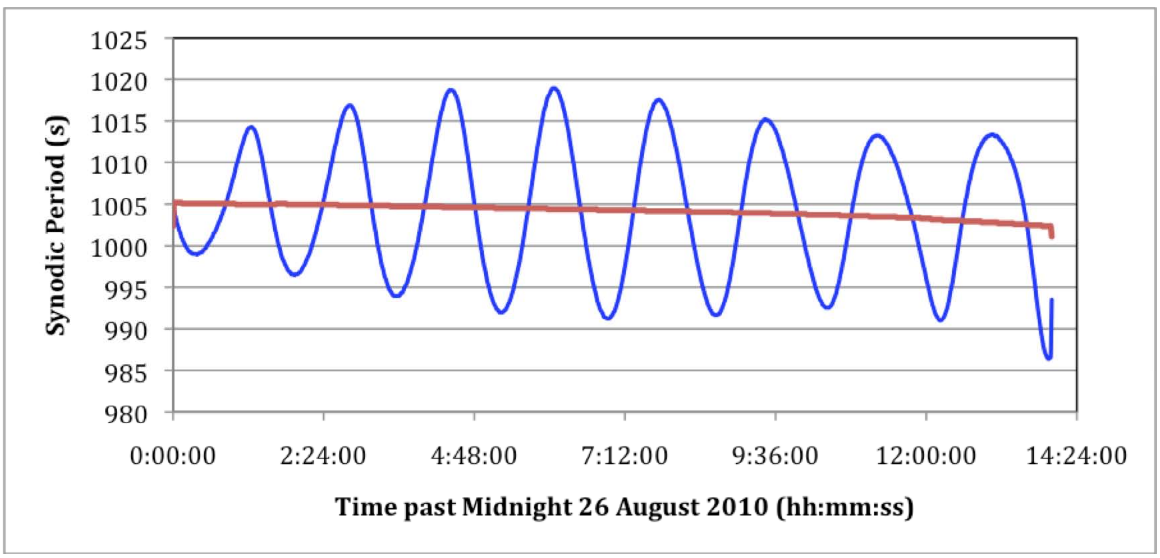

Figure 6: The synodic periods that will be viewed for the modeled situation (see text) from a ground-based (red) and LEO-based (blue) sensor.

The results are shown in Fig. 6, and illustrate the difficulty in measuring the change in synodic period directly from the ground. The period as seen from the ground changes by just 0.3% over this time period, with the result that the method of [3] would require the period at any given time to be measurable to the same precision (a significant challenge). Further, since the object would not be visible to the ground-based observer for the full 14 hours the actual change in synodic period would be even smaller and require correspondingly better precision.

In contrast, the change in synodic period as seen by the space-based sensor is much greater. The oscillations in the blue line in Fig.6 correspond to the orbital period of the observing satellite (i.e. the time between adjacent peaks corresponds to a single orbit of ~100 minutes). Over a half orbit (~50 minutes) the synodic period can change by as much as 2.7%, similar in magnitude to the change that was observed by [3]. This suggests that it may be possible to use a space-based platform to search for the spin state of deep-space objects using the Epoch Method.

The challenge may not be in *whether* we can see the change, but *how* to see it. Specular rotations from a flat panel will typically manifest for roughly 1/10 of the rotation period. During a full NEOSSat orbit, the modeled object will undergo roughly 5 full rotations, but NEOSSat is expected to be able to maintain lock on a given object for only 90-120 seconds before the object drifts out of the field of view and needs to be reacquired (a process that will take roughly 2-3 minutes). The first challenge, then, is that it is entirely possible that individual specular glints could be entirely missed by the sensor. (Note that this limitation can be partially mitigated. Geosynchronous objects will move through a continuous viewing zone, a region of sky that is always visible to the sensor, once a day. Such objects will take ~2 hours to traverse the region, allowing time to collect an uninterrupted sequence of photometry on the objects despite the need for NEOSSat to regularly break lock, and thus present increased opportunities to detect glints).

A second challenge is related to the first. A glint which manifests for roughly 10% of a 1000 s period will last 100s, roughly the same amount of time that NEOSSat will be able to maintain lock on the object. It is therefore likely that any given glint feature will only be partially sampled, and thus the time of the glint peak (and thus the synodic period) will be only poorly determined.

A final challenge is that the memory on board NEOSSat, and its ability to downlink data to the ground, are limited (NEOSSat was not designed for fast imaging experiments). If, for example, the desire was to measure the object brightness every 10 s (in order to sample the specular glint 10 times) the amount of data collected would be more than double what NEOSSat can downlink to the ground.

The question can be asked whether the issues outlined above could be mitigated by looking at a faster spinning object. While this is likely possible to some degree, the rate of change of the synodic period will be smaller for faster spinning objects, and thus the desired effect will be correspondingly harder to detect in the data. As such, the fastest spinning objects - even those with periods on the order or 60 s - are unlikely to be able to have their spin state determined by NEOSSat.

It is also possible that some of these issues could be mitigated by looking at deep-space objects that are not located in geosynchronous orbit. Objects that are located in GPS-like or Molniya orbits, for example, have faster moving PABs. This is clearly an area to be investigated, but these objects will likely present their own observing challenges.

At any rate, it is clear that NEOSSat will require some *a priori* knowledge of the spin periods and light curves of a sample of objects in order to a) identify objects that could potentially have their spin state determined using NEOSSat data, and b) to plan the observations and maximize the probability of acquiring the desired data. Objects that have multiple features in the light curve will be preferable, simply to multiply the chances of detecting a measurable feature. Further modeling is required in order to better identify objects that could be usefully observed by NEOSSat. In preliminary work, we find that slower rotating objects (T_{Sid} ~ 1000 seconds) are better suited to the limited imaging cadence available from the NEOSSat microsatellite. Shape-based approaches, such as the cylindrical models above, may also provide new insights, and the faster moving PAB will reduce the observing time required.

The question can also be reversed. Instead of asking what objects could be usefully observed by NEOSSat in order to determine their spin state, one can ask what would be the characteristics of a space-based sensor that was designed to determine the spin states of deep space objects. While we do not have all of the answers, it is clear that such a sensor should have the ability to actively track an object for extended periods of time (such that the sensor does not have to break lock as NEOSSat will), and should have the ability to make many observations and downlink the results to the ground; this could be done through the use of a large downlink bandwidth, or through the use of on-board processing.

Conclusion

This paper presents a discussion of the challenges in applying the “Epoch Method” to the determination of the spin states on deep-space objects. The challenges stem from the slow change in the sun-object-observer angle, which in turn results in a slow modulation of the synodic spin period of the object.

The paper uses a method based on a small number of shape-based assumptions to determine the spin state of 5 objects; the data were obtained using a small telescope located at the Royal Military College of Canada. A computer model is then used to illustrate the advantages of moving to a space-based sensor in order to obtain similar data in order to apply the Epoch Method without requiring any shape-based assumptions.

There then follows a discussion, based on this model, of the ability to use the NEOSSat spacecraft to obtain data suitable for determination of the spin state of deep-space objects. It is clear that the design of the NEOSSat spacecraft - which was based on the ability to obtain satellite metrics at a low cost - is not optimal for this purpose, but nonetheless NEOSSat has the potential to obtain useful data. More modeling and the collection of ground-based data will be conducted to better select a series of targets to possible observation by NEOSSat.

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